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Comparison study of Trilateral Rankine Cycle, Organic Flash Cycle and basic Organic Rankine Cycle for low grade heat recovery

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Abstract

Organic Rankine Cycle (ORC) has been widely used for the recovery of low-grade heat into power such as solar energy and industrial waste heat. The overall thermal efficiency of ORC is affected by large exergy destruction in the evaporator due to the temperature mismatching between the heat source and working fluid. Trilateral Cycle (TLC) and Organic Flash Cycle (OFC) have been recognized as potential solutions because of their better performance on temperature matching between the heat source and working fluid at the evaporator. In this study, thermodynamic models of above three cycles are established in MATLAB/REFPROP. Results indicate that TLC obtains the largest net power output, thermal efficiency and exergy efficiency of 13.6 kW, 14.8% and 40.8% respectively at the evaporation temperature of 152°C, which is 37% higher than that of BORC (9.9 kW) and 58% higher than that of OFC (8.6 kW). BORC is more suitable under the conditions low evaporation temperature is relatively low due to the achieved maximum net power output, thermal efficiency and exergy efficiency. OFC has the minimum net power output, thermal efficiency and exergy efficiency under all the conditions of evaporation temperature compared to TLC and BORC. As for the UA value, TLC has the largest one ranging from 7.9 kW/°C to 8.8 kW/°C under all conditions while OFC gains the minimum UA value at low evaporation temperature and BORC gains the minimum UA value at high evaporation temperature.

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Keywords: Trilateral Rankine Cycle; Organic Flash Cycle; thermodynamic performance; total heat transfer coefficient

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1. Introduction

The growth of population and economic development causes escalating energy consumption and many other environmental problems by burning fossil fuels [1, 2]. The utilization of low grade heat energy can potential reduce the demand of conventional energy sources and improve the overall efficiency of the existing energy systems [3, 4]. ORCs are considered as a practical solution because of their simplicity, reliability, and flexibility [5-7]. Many researches have been conducted to study the performance of ORC for waste heat recovery [8-11]. However, one of the main problems in ORC based power plants is the high exergy destruction in these cycles. The main source of exergy destruction in ORC is evaporator because of the temperature mismatching between the source and the working fluid [1, 12, 13].

Among the proposed novel cycles, Trilateral Cycle (TLC) is one of the most promising alternatives among the heat recovery-to-power technologies, due to its higher heat transfer efficient from heat source to working fluid, compact system configuration, high performance at relatively low compression work and low-to-moderate expander inlet temperature [14, 15]. For TLCs there are some transformations and organic flash cycle (OFC) is one of the most important system, which can potentially replace the two-phase expander required in TLC and therefore reduce the capital cost of the system [16, 17]. Compared with basic ORCs, which has been widely adopted in the existing power plants, the TLC and OFC are still in a state of technical development. In this paper, the net work power, energy efficiency, exergy efficiency and total heat transfer coefficient of TLC, OFC and ORC have been investigated and compared in order to identify the differences of these systems for various application conditions.

2. System description

2.1. Description of BORC

The schematic and T-S diagram of BORC system are depicted in figure 1. The BORC system consists of an evaporator, a condenser, a pump and an expander. In state 1 the working fluid is saturated liquid with temperature T_1 and pressure p_1 . Then the pressure of the working fluid is elevated to p_2 by the pump with the isentropic pump efficiency $\eta_{sp} = (h_{2s} - h_1) / (h_2 - h_1)$, which is the maximum pressure in the cycle. After that, the liquid is heated to the temperature T_3 in an isobaric process, which is the maximum temperature in the cycle. However it is lower than the critical temperature. The isobaric heating process includes heating of liquid to the saturated state, evaporation of the liquid and finally superheating of the vapor. At state 3 the overheated vapor enters the turbine and expands to the pressure p_4 at state 4 with isotropic expander efficiency $\eta_{se} = (h_4 - h_3) / (h_{4s} - h_3)$ and work is delivered in this process. Eventually, from state 4 the vapor is first precooled to the saturated state with temperature T_1 and then is condensed to state 1 in an isobaric process.

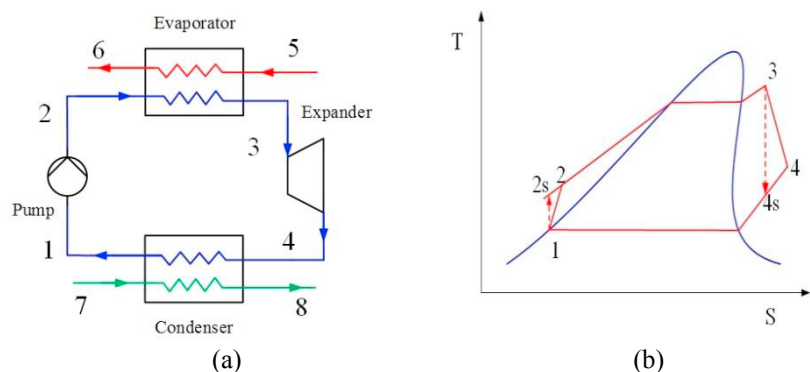


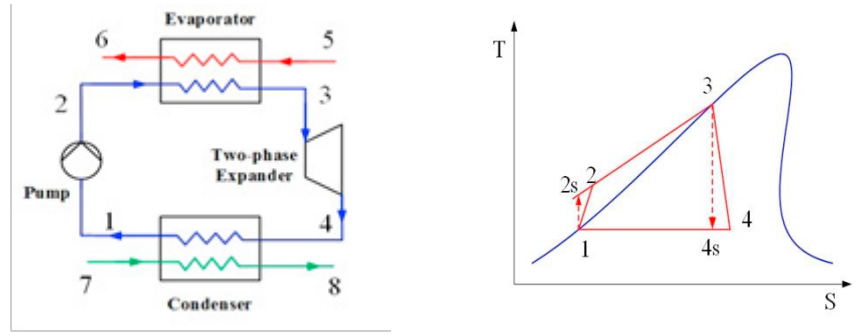
Fig. 1. Basic Organic Rankine cycle

(a) Schematic diagram; (b) T-s diagram

2.2. Description of TLC

The schematic and T-S diagram of TLC system are depicted in figure 2. The TLC system consists of a heat exchanger, a condenser, a pump and a two-phase expander. In state 1 the working fluid is saturated liquid with temperature T_1 at the vapor pressure p_1 . Then the liquid pressure is increased to p_2 by the pump at state 2 in the homogeneous liquid. Thereafter, the working liquid enters the heat exchanger where it is heated to the boiling point

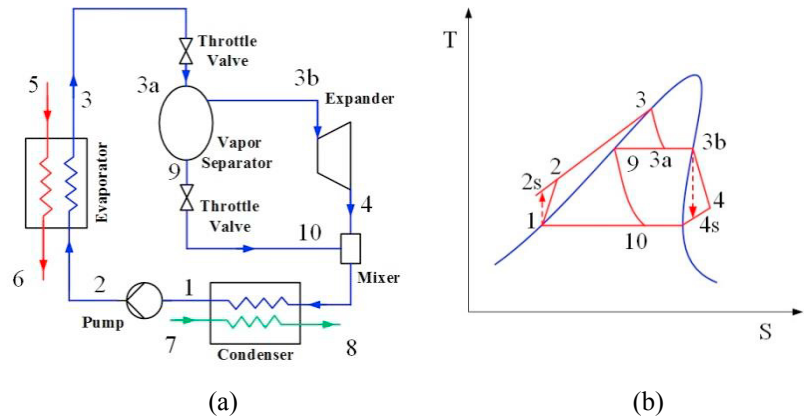
at pressure p_2 , which is state 3. The temperature T_3 is the boiling temperature at pressure p_2 . Starting from state 3, the working fluid directly enters the two-phase expander. In the two-phase expander the working liquid expands into the wet vapor region and gradually reaches the state 4 with the pressure p_1 and temperature T_1 . At state 4 the vapor content is x . during the liquid expanding process work is delivered. Eventually, the wet vapor is completely condensed till it reaches state 1.



(a) (b)
Fig. 2. Trilateral Rankine Cycle
(a) Schematic diagram; (b) T - s diagram

2.3. Description of OFC

System layout and T - s diagram of an OFC are presented in Fig. 3(a) and (b) respectively. Compared to TLC system, in the OFC the saturated working fluid at state 3 is throttled to the expander inlet pressure with isenthalpic process and allowed to enter the vapor separator instead of entering the expander directly. Saturated vapor flowing out the vapor separator expands (from state 3b to 4) in the expander to produce work. Exhausted vapor coming out from expander (state 4) mixes with liquid coming out of throttle (state 9 to 10). Then the total mass of working fluid is condensed to saturated liquid at condenser pressure at the condenser.



(a) (b)
Fig. 3. Organic Flash Cycle
(a) Schematic diagram; (b) T - s diagram

3. Thermodynamic models of the systems

3.1. Thermodynamic model for BORC

For a given mass flow rate of source m_h , the mass flow rates of working fluid m_w and m_c can be determined from the energy balances in the heat exchangers as Eq. (1) and (2), where m is the mass flow rate, T is the temperature, h is the specific enthalpy, and c_p is the isobaric specific heat.

The rate of the heat received by the evaporator Q_{in} , heat

$$m_w = c_{p,h} m_h (T_5 - T_6) / (h_2 - h_3) \quad (1)$$

$$m_w = c_{p,c} m_c (T_8 - T_7) / (h_1 - h_4) \quad (2)$$

$$Q_{in} = m_w (h_2 - h_3) = c_{p,h} m_h (T_5 - T_6) \quad (3)$$

$$Q_{out} = m_w (T_4 - T_1) = c_{p,c} m_c (T_8 - T_7) \quad (4)$$

$$W_e = m_w (h_3 - h_4) \quad (5)$$

$$W_p = m_w (h_2 - h_1) \quad (6)$$

$$W_{net} = W_e - W_p \quad (7)$$

$$\eta_{th} = W_{net} / Q_{in} \quad (8)$$

$$E_{total} = m_w [(h_{in} - h_0) - T_0 (S_{in} - S_0)] \quad (9)$$

$$\eta_{ex} = W_{net} / E_{total} \quad (10)$$

$$UA = \Delta Q / \Delta T_{lm} \quad (11)$$

$$\Delta T_{lm} = (\Delta T_1 - \Delta T_2) / \ln(\Delta T_1 / \Delta T_2) \quad (12)$$

dissipation at condenser Q_{out} , power output from expander W_e , pumping power consumption of the pump W_p , net power output of the cycle W_{net} , thermal efficiency η_{th} , total exergy loss E_{total} and exergy efficiency η_{ex} can be evaluated as Eq. (3)-(7).

The UA (total heat transfer coefficient) value of heat exchangers has been calculated in this study and the calculation method can be defined as Eq. (11), where ΔQ denotes the heat flux of a heat exchanger. ΔT_{lm} denotes the log-mean temperature difference, which can be calculated by log-mean temperature difference method (LMTD) presented in Eq. (12).

$$W_p = m_w h_3 - m_w [x_1 \cdot h_4'' + (1 - x_1) \cdot h_4'] \quad (13)$$

3.2. Thermodynamic model for TLC

$$x_2 = (h_{3b} - h_{3a}) / (h_3 - h_{3a}) \quad (14)$$

The characters of TLC are steps from state 1 to 2 and from state 3 to 4. From state 1 to 2, the liquid is heated to saturated liquid which can be calculated by Eq. (3). Due to the two-phase expander, working liquid at outlet of expander is wet vapor with vapor mass fraction of x_l . The energy conservation equation is defined as Eq. (13)

3.3. Thermodynamic model for OFC

The throttle process from state 3 to 4 determines the mass fraction of vapor x_2 entering the expander. Due to the isenthalpic process, the x_2 can be calculated by equation (14). Other process can be calculated by equation (1) to (12).

Table 1. Initial parameters

Parameters	Value
Inlet temperature of heat source (K)	473
Mass flow rate of heat source (kg/s)	1
Condense temperature (K)	315
Inlet temperature of coolant (K)	298

4. Results and discussion

Working fluid is *R245fa* and calculation is based on the same initial conditions for the three cycles. Some initial parameters are listed in Table 1. Net power output, thermal efficiency, exergy efficiency, *UA* value and total waste heat are evaluated with different evaporation temperature of working fluid. The corresponding results are shown in Fig. 4.

4.1 Evaluation of net power output

Fig. 4(a) shows the net power output increases with the rise of evaporation temperature. OFC has the lowest net power output ranging from 0.6 kW to 8.6 kW at all the operating condition compared to BORC and TLC. The net power output of TLC is first lower than that of BORC with the increasing of evaporation temperature, however, the difference keeps decreasing. When evaporation temperature is beyond 125 °C net power output of TLC is larger than that of BORC. The maximum net power output of TLC (13.6 kW) is 37% higher than that of BORC (9.9 kW) and 58% higher than that of OFC. The results illustrates TLC is more suitable for the waste heat recovery under high evaporation temperature while BORC is well matched to the lower evaporation temperature.

4.2 Evaluation of thermal efficiency

Fig. 4(b) shows the comparison of system thermal efficiency for the three cycles. Thermal efficiency of three cycles improves with the increase of evaporation temperature. The change of thermal efficiency is consistent with the net power output. Thermal efficiency of OFC is lowest ranging from 0.6% to 9.4% under all the operating conditions. Thermal efficiency of TLC is first lower than that of BORC with the rise of evaporation temperature, then it becomes larger than that of BORC when the evaporation temperature exceeds 130 °C. The maximum thermal efficiency of TLC is 14.8% at the evaporation temperature of 153 °C, which is 40% higher than that of

BORC (10.6%) and 57% higher than that of OFC. The results illustrates TLC is more efficient for the waste heat recovery under high evaporation temperature while BORC have better performance at the lower evaporation temperature.

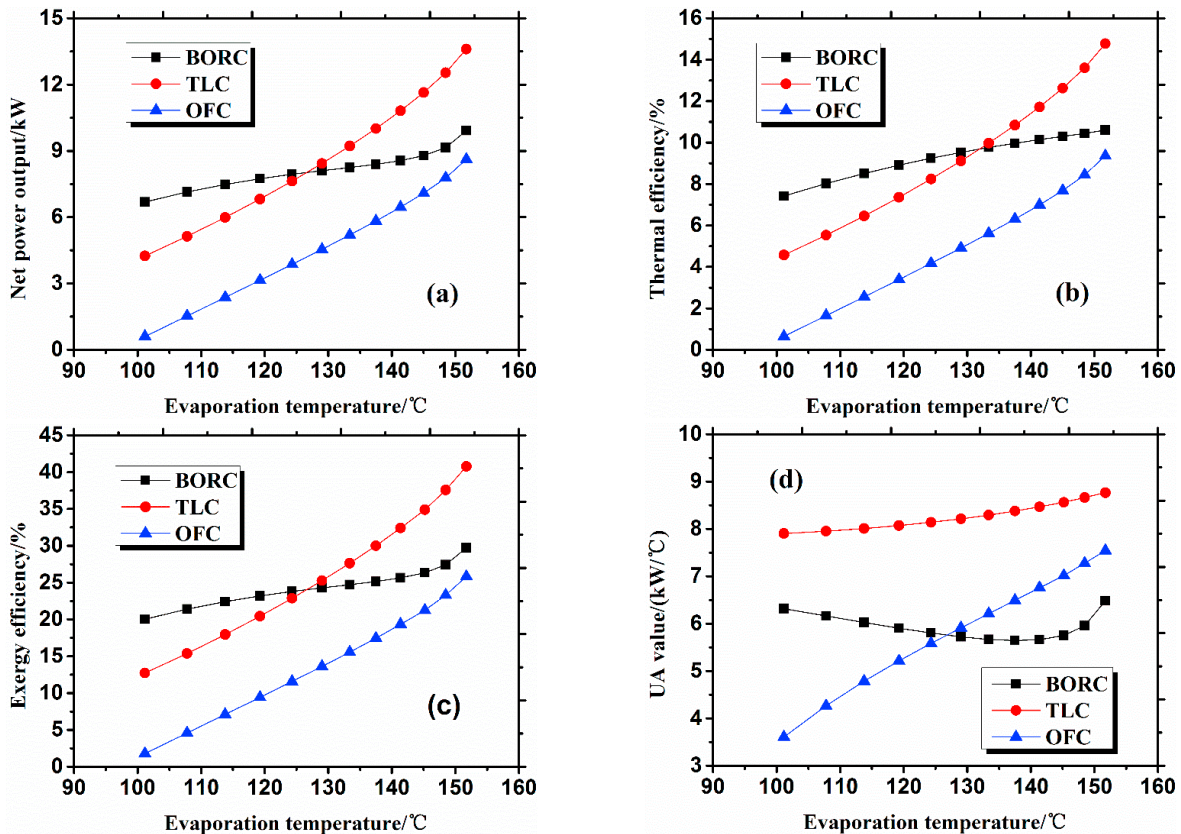


Fig. 4 (a) net power output; (b) thermal efficiency; (c) exergy efficiency; (d) UA value

4.3 Evaluation of exergy efficiency

Similarly, it is observed from Fig. 4(c) exergy efficiency of three cycles keep improving with the rise of evaporation temperature. Exergy efficiency of OFC is lowest ranging from 1.8% to 25.8% under all the operating conditions. Exergy efficiency of TLC is first smaller than that of BORC with the rise of evaporation temperature, then it expands dramatically and when the evaporation temperature exceeds 128 °C it is larger than that of BORC. The exergy efficiency of TLC ranges from 12.7% to 40.8%, indicating the superior property of matching to the heat source. The maximum exergy efficiency of TLC is 37% larger than that of BORC, while the maximum exergy efficiency of BORC is 29.7% and it is 58% larger than that of OFC. Based on the analysis above, it can be concluded TLC is more suitable for conditions with high evaporation temperature while for BORC larger exergy efficiency is achieved at low evaporation in the present study.

4.4 Evaluation of UA value

The smaller UA value means the more economical of the ORC system. It is observed from Fig. 4(d) that the UA value of TLC keeps increasing with the rise of evaporation (ranging from 7.9 kW/°C to 8.8 kW/°C) and it is largest

at all the operating conditions. The UA value of BORC first decreases with the rise of evaporation temperature and reaches the minimum value of $5.7 \text{ kW/}^\circ\text{C}$ at the evaporation temperature of 138°C , then it gradually increases with the rise of evaporation temperature and attains the maximum value of $6.5 \text{ kW/}^\circ\text{C}$ eventually. For the OFC, the UA value rising substantially with the increase of evaporation temperature and ranges from $3.6 \text{ kW/}^\circ\text{C}$ to $7.5 \text{ kW/}^\circ\text{C}$. Comparing the three cycles, OFC has lower UA value at lower evaporation temperature (not beyond 128°C) and BORC has better economic system performance at higher evaporation temperature (beyond 128°C).

5. Conclusions

In the present study, comparative thermodynamic as well as economic analyses under different evaporation temperature are performed for BORC, TLC and OFC while producing power utilizing low grade waste heat of a free flue gas. Conclusions drawn from this study are

1. Net power output increases with the rise of evaporation temperature. OFC has the minimum net power output at all the operating conditions. When the evaporation temperature is higher than 125°C , TLC obtains the maximum net power output 13.6 kW , which is 37% higher than that of BORC (9.9 kW) and 58% higher than that of OFC (8.6 kW).

2. Thermal efficiency has a similar trend to that of net power efficiency for the three cycles. The comparison of thermal efficiency indicates that OFC has the poorest thermal efficiency at all the operating conditions while TLC achieves the best one of 14.8%, which is 40% higher than that of BORC (10.6%) and 57% higher than that of OFC.

3. Exergy efficiency changes consistently with net power output and thermal efficiency. Analysis of exergy efficiency illustrates that OFC has the lowest exergy efficiency at all the operating conditions. Exergy efficiency of TLC is larger than BORC when the evaporation temperature exceeds 128°C and it gains the largest value of 40.8%, which is 37% larger than that of BORC (29.7%) and 58% larger than that of OFC.

4. The UA value of TLC (ranging from $7.9 \text{ kW/}^\circ\text{C}$ to $8.8 \text{ kW/}^\circ\text{C}$) is largest at all the operating conditions. When the evaporation temperature is beyond 128°C , the UA value of BORC is smallest and it reaches the minimum value of $5.7 \text{ kW/}^\circ\text{C}$ at the evaporation temperature of 138°C . When the evaporation temperature is lower than 128°C , OFC obtain the smallest UA value among three cycles.

5. Considering net power, thermal efficiency, exergy efficiency and UA value, TLC has better thermodynamic performance but poor economical overall system performance when the evaporation temperature is beyond 135°C . Reversely, OFC is more economic to be used but the thermodynamic performance is lower than other two cycles.

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Biography

Dr Yiji Lu, born in June 1989, is currently a research associate in Newcastle University. He graduated from Shanghai Jiao Tong University in 2011 for his bachelor degree, he conducted his M.Phil. and Ph.D. in Newcastle University in 2012 and 2016. His Ph.D. program was fully sponsored by EPSRC and was awarded the ‘2015 Chinese Government Award for Outstanding Self-financed Students Abroad’ from China Scholarship Council. His research interests include but not limited to advanced waste heat recovery technologies, engine thermal management, advanced engine development, engine emission technologies, chemisorption cycles and expansion machines for power generation system. He has been regularly invited to review the manuscripts for the scientific journals including Applied Energy, Applied Thermal Engineering, Energy (the International Journal), and Energy for Sustainable Development.

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